GRABEN FORMATION AND DIKE EMPLACEMENT ON EARTH AND OTHER PLANETS. D. Mège[1] and P. Masson[2], [1]Observatoire de Physique du Globe, URA 10 CNRS, Université Blaise-Pascal, 5 rue Kessler, 63038 Clermont-Ferrand, France, e-mail: daniel.mege@geol.u-psud.fr, [2]Laboratoire de Géologie Dynamique de la Terre et des Planètes, URA D1369 CNRS, Bâtiment 509, Université Paris-Sud, 91405 Orsay, France, e-mail: philippe.masson@geol.u-psud.fr.

SUMMARY

Graben formation in the Tharsis province of Mars appears to have been frequently associated to dike emplacement, similar to previous interpretations in volcanic regions on Venus. Relationships between dikes and grabens on Earth suggests that magma pressure may have played a role in locating graben border faults, but not in producing the vertical throws observed.

INTRODUCTION

Dike emplacement has become an increasingly popular means to form grabens radiating from a volcanic centre in the recent planetary geology literature, on Venus [1-3] and on Mars [4-8]. The Tharsis example is used to clarify two important issues that have been scarcely discussed: what evidence of dike emplacement beneath the grabens in the examples mentioned in these papers can be found; and if dikes do actually exist beneath these grabens, what is the role of magma pressure and that of remote stress in graben initiation and development.

EVIDENCE OF DIKES

Graben width and length. Radial grabens in the Tharsis region are segmented, shallow (≤300 m), they have constant width (a few km), and cumulated segment lengths are sometimes more than 2000 km. Mechanically speaking, formation of such long and shallow grabens does not require a special mechanism; it merely requires that, similar to the Earth, the observed fault segments are fractal [9], or in other words, composed of smaller segments which cannot be directly observed from available data [10]. Nevertheless, constant border fault spacing over such long distances, which is theoretically explainable [11], is not observed on Earth, and may have to be explained by some unusual mechanism. Dike emplacement beneath these grabens is an attractive mechanism, because (1) graben formation and dike emplacement both need the same orientation of stress trajectory and the least compressive stress to be horizontal; (2) the state of stress generated by dike emplacement at shallow depth favours fracturing on both sides of dikes [13].

Graben swarm geometry. The radial grabens are fanning and converge toward volcanic centres. This intuitively reminds of giant radiating mafic dike swarms observed in continental shields on Earth such as the Mackenzie dike swarm. There is however no requirement for dikes for explaining geometry of giant graben swarms: gravitational volcanic load superimposed on a regional stress field can produce similar strain geometry [14]. A more convincing argument is that since graben formation is evidence of horizontal least compressive stress, it is likely that magma injection from a central volcanic centre will occur where grabens can form, and the injected magma bodies will normally be dikes parallel to the grabens. The most important requirement is that dike emplacement and graben formation occur under similar principal stress orientation.

Pit craters. Alignment of circular and ovoid pit craters are frequently associated to the Tharsis radial grabens [7, 8]. Pits may result from collapse in tension cracks or pressure drop in dikes (e.g., [5]). Alignments have been observed that are significantly oblique to the direction of the border faults, suggesting that there is no direct structural control on pit formation, which contrasts with the tension crack hypothesis. Report has been made of two curved overlapping segments of pit crater chains in the Tharsis central region, associated to possible lava flows [8], which suggests that pit craters are surface expression of dike tip propagation. The dike hypothesis is also favoured by the apparent absence of huge pit crater formation above tension cracks on Earth reported in the literature, whereas pressure drop in dike is a well-known mechanism or pit crater formation. Examples are found e.g. in Iceland. The enigmatic "jubas" on the Golan Heights aligned with the NNW-trending Golan volcanic chain [15] may have a similar origin.

Fractures associated to pit craters. Occurrence of circular and ovoid pits observed within some radial grabens is most frequently associated to the formation of additional normal faults within the grabens, which have been separated into several categories from geometrical criteria [7, 8]. It was suggested that pits at Alba Patera and Tempe Terra may result from dike emplacement, whereas at Valles Marineris they would result from subsurface tension cracks [5]. However, the fractures associated to the pit craters in the Valles Marineris region were shown to be basically similar to those at Alba Patera and Tempe Terra, suggesting a similar origin. The main difference seems to be that the Valles Marineris pits were more frequently enlarged by wall collapse than in other areas, a feature attributed to the intense erosional activity that took place in the Valles Marineris region during Amazonian [16].

Dike/water interaction along grabens. Flat-floored depressions morphologically similar to thermokarstic depressions on Earth (see [17]) have been found in the Tempe Terra region [8]. Depression alignment and *en échelon* geometry are indicative of a linear zone of ice melting following discontinuities deeper in the crust. Another common morphology is "U"-shaped trough [7, 8, 18], which applies to many usually-called narrow "grabens" that do not display any evidence of normal faulting. Such depressions may have a thermokarstic origin as well. Maars and spatter cones have also been found in the Tempe Terra and Alba Patera/Vastitas Borealis area [8, 19], and alignment with grabens is also evidence of linear magma bodies associated to structural discontinuities. Origin of Mangala Valles in an "U"-shaped trough has been attributed to channelling of magmatic heat by tension cracks from the Tharsis central area [20], but as argued above, the Tharsis volcanic activity is more likely to produce dikes than tension cracks - providing furthermore a far more efficient mechanism of magmatic heat transport [8].

MAGMA PRESSURE AND GRABEN FORMATION

Simple dikes. Elastic modelling shows that magma pressure in simple dikes (i.e., dikes resulting from a single magma pulse) generates tensile stress on both dike sides above its tip, separated by a region where stress is compressive [13]. The predicted style of extensional deformation, using typical dike parameters and a rock-mass failure criterion, is tensile fracturing [21], which is in accordance with field observation (e.g., [22]). Such dikes are thus unable to generate grabens such as those observed on planetary surfaces.

Multiple dikes. Simple dikes are generally thin (less than 1 m). Most dikes thicker than 1 m observed in Iceland are multiple dikes (i.e., resulting from several magma pulses) [23], and probably similar is the case of many dikes in other settings (e.g., [24]). Analog modelling of multiple dike emplacement [12] showed that multiple dike emplacement causes normal faults to nucleate on tensile fractures, resulting in graben formation above dikes. However, dike thickening up to one-half its depth produces vertical fault throws of the order of one-tenth its thickness only. In such cases, driving pressure, which is proportional to dike thickness (e.g., [25]), would be large enough to cause dike eruption, and grabens would be very small. Once such dikes would have reached the surface, grabens would stop deepening, because magma overpressure would first tend to lock the faults [26], and then would rapidly decrease to zero. Not only do most radial grabens on Mars not display any evidence of associated volcanic flows, but also should grabens that would possibly form not be observed on the currently available images.

Furthermore, extensive field work in Iceland could not succeed in finding any graben of whatever size associated to either simple or multiple dikes (e.g., [23]). The reason is that each magma sheet intrudes the centre of the formerly injected magma sheets forming the dike. Emplacement of each sheet produces tensile stress above its tip, partly released through fracturing, allowing each new magma sheet to reach a shallower crustal level. Following this mechanism [23], the maximum tensile stress at the upper dike tip is always more or less equal to the tensile stress generated by the last magma pulse, and therefore, never large enough to cause graben formation. This mechanism is in agreement with observation that most dikes in Iceland end vertically by tapering away. Thus, emplacement of thick dikes does probably not alter the results obtained for thin dikes.

CONCLUSION

Many narrow grabens on planetary surfaces appear to be located above dikes, probably of mafic composition because of their length. The role of dike magma pressure in graben development is probably negligible, although the stress generated in the host rock may have influenced border fault location. Most fault vertical throws should have resulted from remote tensile stress, working either contemporaneous to, or later than dike emplacement. Formation of grabens after dike freezing is possible, and would be explained by remote tensile stress concentration at the dikes due to dike Young's modulus higher than in the host rock. Boundary element modelling of dike emplacement and graben formation is in progress and should help better understanding these issues.

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